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Using Laser Scanners to Augment the Systematic Error Pointing Model

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ABSTRACT. — The antennas of the Deep Space Network (DSN) rely on precise pointing algorithms to communicate with spacecraft that are billions of miles away. Although the existing systematic error pointing model is effective at reducing blind pointing errors due to static misalignments, several of its terms have a strong dependence on seasonal and even daily thermal variation and are thus not easily modeled. Changes in the thermal state of the structure create a separation from the model and introduce a varying pointing offset. Compensating for this varying offset is possible by augmenting the pointing model with laser scanners. In this approach, laser scanners mounted to the alidade measure structural displacements while a series of transformations generate correction angles. Two sets of experiments were conducted in August 2015 using commercially available laser scanners. When compared with historical monopulse corrections under similar conditions, the computed corrections are within 3 mdeg of the mean. However, although the results show promise, several key challenges relating to the sensitivity of the optical equipment to sunlight render an implementation of this approach impractical. Other measurement devices such as inclinometers may be implementable at a significantly lower cost.

I. Introduction

Although monopulse can significantly reduce pointing errors, not all applications are able to utilize this RF-based pointing error compensation technique. Acquisition and very long baseline interferometry (VLBI) can benefit greatly from improvements in blind pointing error performance. Currently, a systematic error model is used to account for pointing misalignments. However, obtaining an accurate model requires a lengthy calibration process. Although the residual errors become very small immediately after a calibration, the errors tend to increase seasonally and, to some extent, even daily. This is because a subset of the model parameters that relate to the structural alignment depend on the temperature, humidity, wind conditions, and solar radiation exposure. These are the set of conditions that drive the thermal state of the antenna.

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Since the current pointing model captures a snapshot at only one thermal state, as the conditions change, the structure diverges from the model and generates a pointing error. With a careful selection of sensor locations, a precision laser scanner system can measure these divergences and determine an appropriate pointing offset. This changing offset can then be injected into the position controller for real-time compensation.

II. Characterizing the Error Model

Before defining the laser system and choosing sensor locations, the antenna's structural motion must first be characterized. The existing systematic error model has 118 terms, most of which are strictly mathematical, having no physical manifestation. If all of the mathematical terms are ignored and we select the terms that are likely to vary with the thermal state, the model can be significantly simplified. Ignoring translations, four angles can define a nonideal azimuth/elevation (AZ/EL) axes set. The AZ axis can be tilted in the north/south or east/west directions. The EL axis can be nonorthogonal to AZ. The EL reference plane can be pitched up or down. With these four parameters and the current AZ and EL encoder angles, EL and cross-elevation (XEL) offsets can be computed using basic trigonometry.

Before computing the pointing offsets, the misalignment angles must be determined from the laser sensor outputs. The sensors work by measuring the displacement of an incident laser plane in a 25-mm window. Four sensors and two planes were needed to fully characterize this model. Some more basic trigonometry was used to compute the axis tilt and skew angles from the measured displacements. See Figure 1(a) and Figure 1(b) for the sensor and reference plane mounting locations.

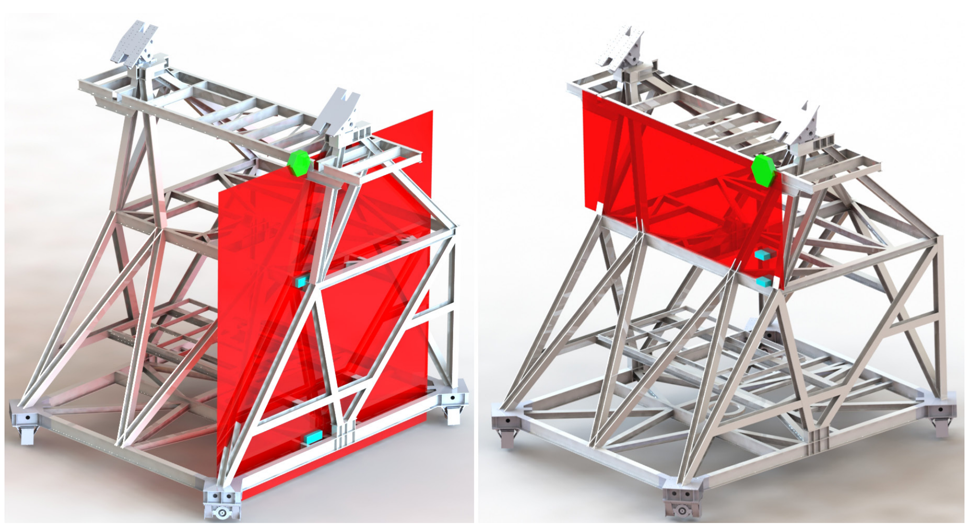

Figure 1. Experimental configuration. The green octagon represents the scanning laser plane source and the small teal rectangles represent the incident sensors.

With these sensor locations in mind, the following system of equations can be generated:

$$\begin{aligned}
\delta_{t_1} + \delta_{s_1} &= \delta_1 \qquad & \delta_{t_2} l_{t1} - \delta_{t_1} l_{t2} &= 0 \\
\delta_{t_2} + \delta_{s_2} &= \delta_2 \qquad & \delta_{s_2} l_{s1} - \delta_{s_1} l_{s2} &= 0 \\
\delta_{t_3} + \delta_{s_3} &= \delta_3 \qquad & \delta_{t_4} l_{t3} - \delta_{t_3} l_{t4} &= 0 \\
\delta_{t_4} + \delta_{s_4} &= \delta_4 \qquad & \delta_{s_4} l_{s3} - \delta_{s_3} l_{s4} &= 0
\end{aligned}$$

where l_{t_i} and l_{s_i} represent the vertical distance from sensor i to the pintle bearing and EL axis of rotation, respectively, and δ_i is the sensor output. Since there was no absolute reference, the sensors were calibrated such that the computed pointing offsets were zero at the start of each experiment. At each timestep, this 8×8 system of equations is solved and then the pointing offsets are calculated using the following:

North–South Tilt:

$$\theta_{NS} = \frac{\delta_{t_2}}{l_{t_2}} \sin(AZ) + \frac{\delta_{t_4}}{l_{t_4}} \cos(AZ)$$

East–West Tilt:

$$\theta_{EW} = \frac{\delta_{t_2}}{l_{t_2}} \cos(AZ) - \frac{\delta_{t_4}}{l_{t_4}} \sin(AZ)$$

Axis Skew:

$$\theta_{SK1} = \frac{\delta_{s_2}}{l_{s_2}}$$

EL Offset:

$$\theta_{SK2} = \frac{\delta_{s_4}}{l_{s_4}}$$

$$\begin{bmatrix} \Delta EL \\ \Delta XEL \end{bmatrix} = \begin{bmatrix} \cos AZ & -\sin(AZ) & 0 & 1 \\ \sin(EL)\sin(AZ) & \sin(EL)\cos(AZ) & \sin(EL) & 0 \end{bmatrix} \begin{bmatrix} \theta_{NS} \\ \theta_{EW} \\ \theta_{SK1} \\ \theta_{SK2} \end{bmatrix}$$

III. Initial Results and Discussion

The first of the two experiments under this configuration involved slewing the antenna along a trajectory that traces back on itself several times. The goal of this test was to show how repeatable the system is and how noisy the readings are when the antenna is at peak rate. The antenna trajectory, along with the computed AZ and EL corrections, are shown in Figure 2. In order to ensure a static thermal state, these tests were conducted several hours before sunrise on a day with very little wind.

Even though some change in output is expected even for the same antenna attitude, the corrections are very repeatable. The differences seen throughout the experiment were less than 1 mdeg and are a direct result of structural displacements taking place during motion. The stable nighttime conditions make it unlikely for the differences to be due to rapid changes in the thermal state of the structure.

Although EL movement generates little noise in either correction, at slew, AZ generates 2-mdeg and 4-mdeg chatter on the AZ and EL corrections, respectively. This noise level suggests that a mode-switching controller may be needed to reject the corrections when used at frequencies higher than 8.5-GHz (X-band).

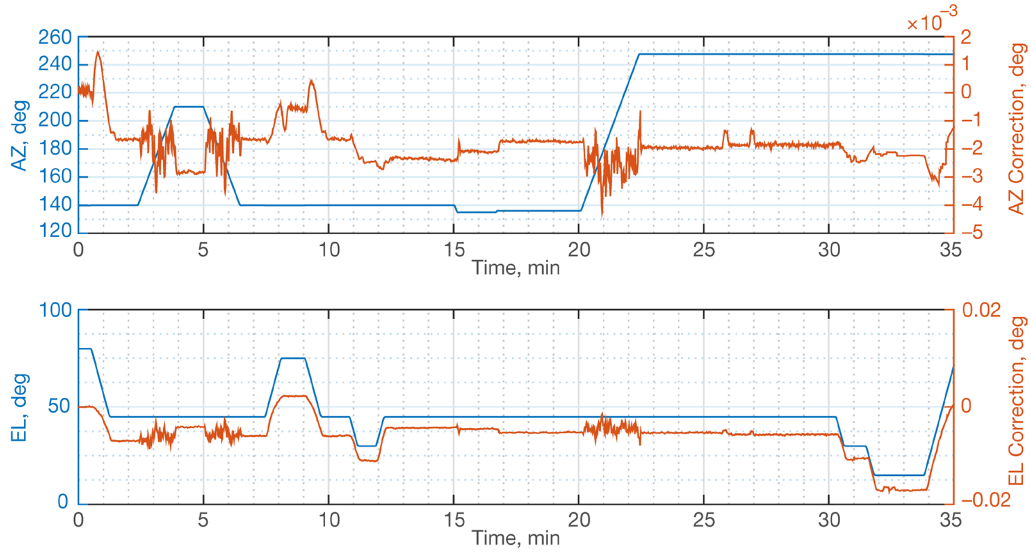

Figure 2. Antenna trajectory and computed corrections during motion experiment.

In the second experiment, the antenna was left stationary for several hours before and after sunrise. In order to exaggerate the effect of the sunrise, the antenna azimuth was oriented 180 deg away from where the Sun was to rise and elevation set to 45 deg. This ensured that the reflector surface would not shade the structure when the Sun appeared. The goal of this test was to show the magnitude of the pointing offset that is induced by the transitory sunrise period. The XEL and EL corrections, along with the local weather tower ambient air temperature, are shown in Figure 3.

Although not much can be correlated between the ambient air temperature and the resulting corrections, a sharp jump can be seen in both outputs about 4 to 5 min after sunrise. That is because the primary source for an increase in surface temperature on a steel structure is solar radiation [1]. The ambient air temperature plays a smaller role in determining the surface temperature and thus its effect on nodal displacement is also smaller. However, the spike is not entirely caused by the solar radiation. It includes a reading going outside of the measurement range on one of the four sensors. This is likely due to nonideal placement of the sensor that resulted in an increased sensitivity to sunlight. Per recommendation from the laser scanner manufacturer, future tests should ensure that all sensors are mounted within 10 deg of the scanned plane. Despite the interference, the measurement recovered with valid readings and revealed a 1.5-mdeg shift in XEL and 15.3-mdeg in EL.

Unfortunately, without an RF-based pointing offset measurement during this time period and on this antenna, there is no way of knowing if these results are accurate. Future investigations should include monopulse or boresight datasets to evaluate the accuracy of this approach. Nonetheless, in order to determine if the results could be accurate, the laser data will be compared with historical pointing corrections obtained using monopulse. This is explored in the following section.

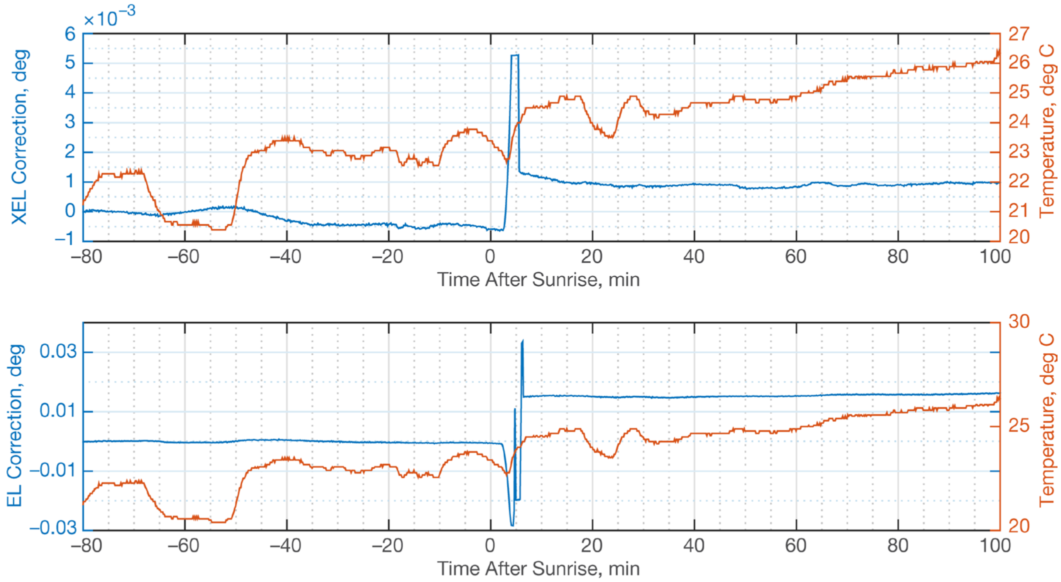

Figure 3. Antenna computed corrections during sunrise experiment.

IV. Comparison with Monopulse Data

Figure 4 presents data that were collected on operational DSN antennas at the three complexes and across 55 tracks that overlap sunrise.[1] They show EL and XEL corrections plotted against a timescale relative to the local sunrise time estimated by a tool provided by Scripps Institution of Oceanography [2].

The black mean trend lines show that the corrections are relatively stable in the hours before sunrise but begin changing shortly thereafter. Three hours after sunrise, the mean EL correction settles to 13 mdeg with a standard deviation of 6.9 mdeg, while the XEL correction averages 2 mdeg with a standard deviation of 4.5 mdeg.

The computed offsets from the laser data are well within one standard deviation of the monopulse data shown in Figure 4. Although this suggests that the steady-state output of the model may be accurate, timescale comparisons from Figure 3 and Figure 4 show different rates of change of the corrections. A 13-mdeg shift over 3 hours is quite different from 15 mdeg over 10 minutes. Even in the most rapid of the 55 datasets, 15 mdeg worth of offset took about an hour to reach. This suggests that other factors are involved. In the laser tests, EL and XEL offsets are computed from deflections measured on the alidade, while the monopulse corrections are not limited in such a way. It is possible that these other factors contribute in a way that dampens the offset from the alidade measurements. Lastly, the experiment held the antenna at a fixed azimuth while the datasets were collected while the antenna was tracking. The stationary antenna is likely to have developed a more extreme pointing offset since the solar radiation is concentrated on a smaller percentage of the structure.

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[1] Timothy Pham, DSN Performance Analysis — Antenna Pointing, http://dsnpar.jpl.nasa.gov/mono.raw (JPL internal website), Jet Propulsion Laboratory, Pasadena, California, 2016.

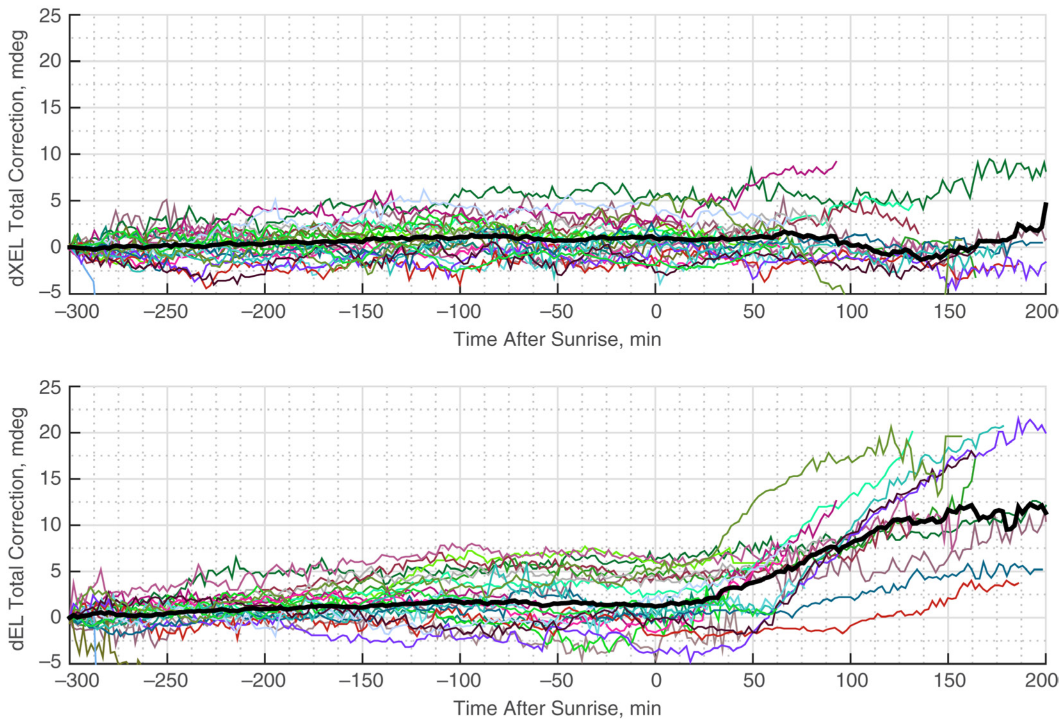

Figure 4. Total elevation and cross-elevation correction during sunrise.

V. Considerations and Conclusions

Although the laser system shows promise, this investigation shows that an implementation would require several additional design details.

(1) The sensors must be calibrated appropriately to avoid introducing a fixed bias to the offsets.

(2) Static systematic error model terms used in the laser approach need to be backed out of the existing model to avoid overcorrecting.

(3) A mode-switching algorithm will be needed to smooth out the transients when the sensor noise becomes high.

(4) The equipment must be protected from the rain and direct sunlight without interfering with the optical path.

Although the first three are common with any other dynamic pointing model approach, the fourth is unique to this laser-based approach. Due to the large footprint of this system, developing these environmental protection enclosures would be a significant hurdle in its implementation. Coupled with the already high relative-cost of the optical sensors, augmenting the systematic error model with laser scanners is unlikely to be a cost-effective solution. Ongoing parallel efforts using inclinometers have shown similar results at a substantially lower cost.

Acknowledgments

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[1] Thaksin Thepchatri, C. Philip Johnson, and Hudson Matlock, *Prediction of Temperature and Stresses in Highway Bridges by a Numerical Procedure Using Daily Weather Reports*, Report No. FHWATX-77-23-1 (Interim Report), The Center for Highway Research, University of Texas at Austin, February 1977.
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[2] Rich Pawlowicz, Suncycle, Scripps Institution of Oceanography, 2016.
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